

USARIEM TECHNICAL REPORT T01-11

**THE IMPACT OF LOAD AND GRADE ON ENERGY EXPENDITURE
DURING LOAD CARRIAGE, PART II: FIELD STUDY**

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13. ABSTRACT (Maximum 200 words) The metabolic costs of load carriage were measured for 8 volunteers on uphill, level and downhill grades at Yakima Training Center (YTC). Volunteers carried loads of 0, 13.6 or 27.2 kg as they walked on grades of 0% (level), $\pm 4\%$, $\pm 8.6\%$ and -12% at 3 mph. Mean values for oxygen consumption (VO ₂) during load carriage indicate costs increased with increasing load and uphill grade, and decreased with negative grades. A mathematical model, using a terrain factor of 1.1 for sites with gravel, was used to calculate load carriage costs. Those values were compared to field data. Results for the negative data showed no significant difference between the model and downhill measurements. For the $+8.6\%$ grade there was a significant difference between the measured and model calculated values, which underestimated the measured costs. Results obtained under field conditions were also compared to results obtained under laboratory conditions on treadmill grades of 0%, $\pm 4\%$, $\pm 8\%$ and -12% . When the field data were compared to laboratory values, the field data were also higher than the laboratory data. It is possible that the difference between observed and model calculated values reflects a difference between laboratory and field conditions.				
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TABLE OF CONTENTS

<u>SECTION</u>	<u>PAGE</u>
LIST OF FIGURES.....	v
LIST OF TABLES.....	v
BACKGROUND	vi
ACKNOWLEDGMENTS.....	vii
EXECUTIVE SUMMARY	1
INTRODUCTION	3
PURPOSE.....	3
MILITARY RELEVANCE	3
GENERAL	3
FIELD STUDY	5
Load Limits	6
MODELING	6
METHODS	7
VOLUNTEERS	7
PRE-TESTING	7
FIELD STUDY PLAN.....	7
Study Locations	7
Data Collection	8
FIELD TESTING SCHEDULE	9
MODELING	9
RESULTS	11
SUBJECT POPULATION.....	11
STUDY CONDITIONS.....	11
OXYLOG PERFORMANCE	12
DATA MATRIX	12
DATA ANALYSIS	12
COMPARISON TO LABORATORY DATA.....	15
APPLICATION OF THE TERRAIN FACTOR	17
MODELING VALUES.....	17
Statistical Results	17
DISCUSSION	22

CONCLUSIONS.....	24
RECOMMENDATIONS.....	25
REFERENCES.....	26

LIST OF FIGURES

<u>FIGURE</u>		<u>PAGE</u>
1	Energy costs of treadmill load carriage at 1.34 m/s	5
2	Oxygen uptake for all loads by grade (1.5 SD filter)	13
3	Comparison of field and laboratory results (zero load)	15
4	Comparison of field and estimated laboratory results (13.6 kg load)	16
5	Comparison of field data to modeling results (zero load)	19
6	Comparison of field data to modeling results (13.6 kg load)	20
7	Comparison of field data to modeling results (27.2 kg load)	21

LIST OF TABLES

<u>TABLE</u>		<u>PAGE</u>
1	Description of test sites at Yakima Training Center (YTC)	8
2	Subject population dimensions	11
3	Weather condition during data collection	11
4	Mean oxygen uptake (mlO ₂ /kg/min) by load	14
5	Field data and model calculations	18

BACKGROUND

The development of predictive models is an assigned mission of USARIEM under STO3U. This study was in response to a specific need for input into models being developed by USARIEM and for cooperative projects with other organizations such as the IUSS being developed by the U.S. Army Soldier Biological and Chemical Command (SBCCOM). The data collected during Phase II was used to evaluate a model developed from data collected during Phase I and will be used to validate other models under development. The telemetry temperature pill and activity monitor are prototype components of the Warfighter Physiological Status Monitor (WPSM). This study also presented an opportunity to expand the performance database for these sensors during controlled field use.

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EXECUTIVE SUMMARY

This study is an expansion of a previous laboratory study that measured the metabolic energy requirements of load carriage over positive (uphill), level and negative (downhill) grades. By expanding the limited data for load carriage over sloped terrain to include field tests, this study provides a database for testing predictive modeling programs of soldier performance under field conditions.

Prior to field testing, maximal oxygen uptake ($\text{VO}_{2\text{max}}$) and percent body fat were determined for each subject. Field testing was conducted at Yakima Training Center (YTC) in May, 2000. Volunteers carried loads of 0 kg, 13.6 kg or 27.2 kg in rucksacks as they walked on level and downhill grades of 0%, 4%, 8.6% and 12%. Subjects also attempted uphill load carries with all 3 loads on the 8.6% grade and with empty (zero load) packs on the uphill 4% grade. The level site was a paved airstrip. The 4% and 8.6% sites were graded gravel roads, while the 12% grade was more of a rock and gravel track. Subjects were paced at $1.34 \text{ m}\cdot\text{s}^{-1}$ (3 mph) for all measurements. Slopes were of sufficient length to obtain steady state values for oxygen consumption (ml/kg/min) by allowing subjects to walk steadily for 13 - 20 min. Oxygen uptake was collected using portable oxygen monitors.

Core temperatures (T_c) were measured with an ingested pill and displayed on a recording device carried by each subject. The temperature pill is a proposed component of the Warfighter Physiological Status Monitor (WPSM). Heart rates were also monitored. Environmental conditions (air temperature, humidity and radiation) were measured with a portable weather station and WBGT monitor during testing.

Mean values for oxygen consumption during load carriage indicate it increased with increasing uphill grade and load, and decreased with negative grades. Differences in oxygen consumption were much smaller for downhill load carriages, and data variances were greater. Thus, relative to uphill load carriage differences between grades and loads, downhill load carriage energy costs often appear to be near constant when plotted together.

Results obtained under field conditions were compared to mean results ($n=16$) obtained under laboratory conditions for zero load packs on treadmill grades of 0% (level), $\pm 4\%$, $\pm 8\%$ and -12% . The oxygen consumption rates collected in the laboratory for 9.1 kg and 18.1 kg loads were averaged to estimate the cost of carrying 13.6 kg loads under laboratory conditions. Linear interpolation was used to estimate the laboratory equivalent of an 8.6% grade from the measured 8% grade data.

Terrain factors for different surfaces may be obtained from the literature (13). The adjustment from a level paved surface to dirt is 1.1. The laboratory values were multiplied by the terrain factor, and then compared to the field data. Inspection of the plotted data suggests that the terrain factor for dirt surfaces was somewhat low. There is also a trend in the data that indicates that the terrain effect may not be linear as grades become more extreme. However, an alternative explanation is that the deflection of high and low end measurements may be an artifact of the oxygen monitor (6).

A model was derived from the laboratory values. The mean subject weight (80.2 kg) was used as the model input to calculate load carriage energy costs. Those values were multiplied by the dirt terrain factor value (1.1) and compared to the field data. The data were split into 3 subsets for statistical analysis: all negative and level data, all level and uphill data with zero load, and all loads on the 8.6% uphill grade.

Results for the negative data set showed no significant difference between the measured vs. the downhill modeling results. Load and grade were highly significant overall, and there were significant interactions for grade vs. load and grade vs. type, thus indicating that data points for load and grade were discrete.

Results for the single (zero) load, multi-slope data set also indicated no significant differences between measured and calculated values. For the uphill, no load subset, grade and the interaction between grade and type were highly significant. For the 8.6% grade with all loads, load and type were significant. Thus, for the 8.6% uphill grade, there was a significant difference between the measured and model calculated values. The model underestimates the measured VO_2 for the 8.6% grade. However, when field data were compared to laboratory values, the field data were also higher than the laboratory data. It is possible that the difference between observed and model calculated values reflects a difference between laboratory and field conditions, including a difference between instruments for measuring VO_2 .

INTRODUCTION

PURPOSE

This study is a continuation of a research program to quantify the metabolic cost of load carriage by expanding the database to quantify energy expenditure during load carriage over positive (uphill), level (0-grade) and negative (downhill) slopes under field condition. Individual data collected included volume of oxygen (VO_2) consumed and heart rate (HR). Data gathered from this study will be incorporated into predictive models, including SCENARIO (3) and the physiological module developed for the Integrated Unit Soldier Simulation (11). At present, these predictive tools are limited in their ability to accurately predict energy expenditure for locomotion over negatively sloped terrain.

MILITARY RELEVANCE

Metabolic costs are important to soldier performance in several ways. A soldier has limited energy reserves. If an activity has a certain energy requirement, and there are insufficient energy reserves available, the soldier either may not be able to perform that task or the level of performance may be reduced. A second level of concern is thermal stress. As the body converts or metabolizes stored chemical energy into mechanical energy, heat is generated as a by-product. In cold weather, extra heat may be an advantage, but in a warm environment, and especially during heavy exercise in NBC clothing, the soldier could become a heat casualty. It is important to know the energy costs of activities.

GENERAL

While walking on the level grade at a constant speed, energy costs increase as the load increases, but because the load is only temporarily displaced in a vertical plane with no net change in vertical displacement, no external work is performed against gravity. When moving uphill on a constant slope at a given speed and time, there is a vertical lift, and work is performed against gravity. The load includes body mass. On a downhill or negative slope, gravity pushes the load downhill a vertical distance, thereby reducing the cost of load carriage relative to level load carriage. The cost of moving a load up or downhill on a slope is theoretically equivalent to a simple vertical lift or drop of the same height, but the efficiency or inefficiency varies to some degree with differences in slope and/or frictional forces. In downhill movement, negative work may result in acceleration of the individual as gravity exerts a downhill push until he/she loses control and falls. Instability during downhill movement occurs whenever forward momentum overcomes the resistance to acceleration or deflection provided by the total mass. Carrying a load increases the initial resistance to acceleration and deflection by increasing total mass. Thus, to some extent, instability is countered by the weight and load of a person, but as total mass increases, the difficulty in controlling or countering the acceleration or deflection should also increase. An individual with a pack load of 13.6 kg may in fact be more stable than either a person with no load or a 27.2 kg load for a given walking speed.

The majority of studies incorporating load carriage energetics were conducted on level or uphill grades. In the real world, for any given number of loads that are carried

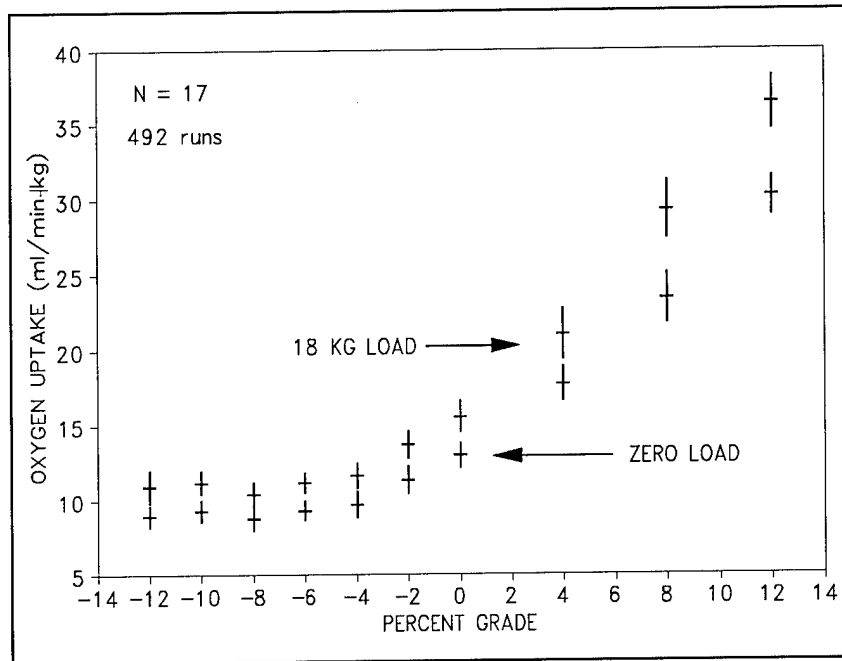
uphill over undulating terrain, an equal number will be carried approximately the same distance downhill. Thus, in terms of slope, it could be said that the world tends towards equilibrium. Consequently, to develop a comprehensive estimate of total energy requirements and expenditures, if the energy costs of downhill load carriage were significantly different from load carriage on the level, there would be a continuing need to develop and refine models that included downhill movement.

The lack of data on downhill load carriage may be attributable to several factors: a lack of suitable treadmills or outdoor study sites, a reduced interest in the less demanding downhill task relative to level and uphill movement, and the problem of addressing the interaction of the downhill push of gravity and the braking to maintain balance and control (stability). In addition, there is a concern that downhill load carriage with heavier loads will increase the possibility of subject injury due to falls or muscular or skeletal strain.

Earlier investigators (4, 5, 14) had observed that the minimum energy requirement occurred on a negative slope. Data from the 1998 laboratory study (12) found that for most of the subjects, minimum oxygen uptake occurred on an -8% grade (Figure 1). This finding tends to support Margaria (4), who suggested that the minimum value would occur on a -9% grade, versus Wanta et al. (14), who indicated that location of the minimum (nadir) would vary according to individual characteristics. Minetti et al. (5) presented a biomechanical analysis of graded walking that indicated a nadir of 10.2%. Due to the large variance, the plot indicates trends rather than statistically valid differences between adjacent grades. However, the 2 most interesting aspects of the data for negative slopes are (1) the minimum or nadir at -8% and (2) the apparent downward shift in the data between -10% and -12% grades. This change, if replicable in other studies, has been tentatively interpreted as the interaction of braking and the downward push of gravity. The Doriot chamber treadmills cannot be run at slopes greater than 12% grade. Unfortunately, field sites of sufficient length to allow a 15-20 min downhill run at a constant slope greater than 12% are also rare. Consequently, the option of testing on a steeper slope is not a viable option.

Questions regarding downhill load carriage may not be resolved by a single study. Two variables were not addressed in Phase II: walking speed and a wider range of backpack loads. However, to establish the validity of applying the results of a laboratory study (Phase I) to field conditions requires that the field study follow the general design of Phase I. Thus, the same walking speed ($1.34 \text{ m}\cdot\text{s}^{-1}$) and grades (0, 4, 8, 12%) will be incorporated. An empirical model has been developed from the Phase I data. The model is based on corrections for positive and negative work to an initial prediction of the metabolic costs of zero load on a level surface, so walking on the level track establishes baseline values on a specific surface/substrate. The predictive model initially derived from the Phase I data uses load as a variable, but not walking speed. Consequently, it would be possible to vary the loads and still use the same model, but it is less certain that the model will be valid for different walking speeds.

Figure 1. Energy costs of treadmill load carriage at 1.34 m/s



FIELD STUDY

The laboratory study demonstrated the advantages of control and instrumentation during treadmill walking. An important question about any laboratory study is, How well do results translate to a more realistic environment? The control of grade is certain in the laboratory chamber, whereas a consistent grade is virtually non-existent in an outside environment.

Two basic approaches to expanding the scope of the database were considered. The alternatives were to increase the backpack load, or to alter the speed of the descent. Decreasing the speed of the descent may increase the inertia of the subject and may thereby lower the required braking effort. Increasing the speed of descent increases the possibility of loss of control or stability by the subject, and may thus increase the likelihood of falls and injury. Increasing the weight of the backpack should increase the downward force due to gravity, which may also increase the likelihood of falls if the speed of descent remains at $1.34 \text{ m}\cdot\text{s}^{-1}$. However, the braking effort required to offset the increased downward force due to gravity may be reduced by the increasing difficulty of walking due to a greater total mass. Thus, shifting the onset and magnitude of the braking effort may be modified with heavier loads.

That interpretation is speculative and is based on an observation that walking effort increases with an extremely heavy pack. With a heavy load, it is difficult to just take a step, even with some forward momentum. Hence, it also becomes more difficult to achieve the temporary vertical displacement involved in stepping forward, even though the downward force or push increases with a heavier load. When walking downhill with light

loads, the problem, due to momentum and gravity, is to control speed and balance. With a very heavy load the problem of control and instability may increase, or it may be "dampened" by the difficulty of stepping forward. If the conditions were a 70 kg subject carrying a 91 kg load (130% of body weight) at $0.7 \text{ m}\cdot\text{s}^{-1}$ on a 8% grade, would the subject need to brake to control his/her descent? Our test conditions are different, but Charteris (1), has indicated that even level walking with varying loads is complex modeling.

Load Limits

Knapik (2) cites a U.S. Army objective to limit a total load to 33 kg for the approach march load, but also notes that actual loads for light infantry soldiers ranged from 56-76 kg. The selection of a maximum rucksack load of 27.2 kg was chosen based on Knapik's (2) indication that U.S. Army doctrine recommended a total approach march load of 33 kg. USARIEM load carriage studies, in response to observations of actual soldier loads, often exceed the 33 kg target. The total load value includes the weight of all clothing and equipment including instruments -- an additional 8.8 kg. Thus, the maximum total load for this study is 36 kg.

There was some concern that the maximum load for this phase of the study should be greater. Patton et al. (10) for example used external loads up to 49.4 kg (109 lbs). However, if the walking speed is maintained at $1.34 \text{ m}\cdot\text{s}^{-1}$, there is reason to believe that a heavier load (49 kg) would increase the possibility of a fall and/or injury to the subjects. In addition, in Phase I, some subjects were already at their maximum capability for uphill load carriage with an 18.1 kg load on a 12% grade.

MODELING

Data gathered during this study partially fulfill the need for a database to test and refine predictive equation(s) for the metabolic cost of soldiers performing load carriage over different slopes and varying terrain. The energy expenditure model to be evaluated was developed from the database from Phase I of this study (12).

METHODS

VOLUNTEERS

Eight (8) healthy volunteers were recruited from the U.S. Army Soldier Biological and Chemical Command (SBCCOM) Headquarters Test Volunteer Detachment and USARIEM. Prospective subjects were informed of the purpose, procedures and risks of the study and expressed their understanding by signing a statement of informed consent. Each volunteer then was cleared by a medical officer.

PRE-TESTING

Prior to travel to the field test site, volunteers performed a continuous treadmill maximal oxygen uptake (VO_2max) test (7). Height, weight and age were recorded for each subject. To obtain fat-free body mass, subjects also underwent a low-dose dual energy X-ray absorptiometry (DEXA) measurement.

FIELD TEST PLAN

Preliminary data were collected at USARIEM before traveling to the field site. All field testing was done at YTC in eastern Washington. The plan was scheduled for mid-spring, after the winter thaw, while air temperatures were expected to be moderate. To ensure that subjects are not exposed to a significant potential for heat strain, no test session was started if the Wet Bulb Globe Temperature index (WBGT) exceeded 78°F.

Study Locations

YTC was selected as a test site based on information provided by the U.S. Army Topographic Engineering Center (TEC). We asked TEC to identify military sites with consistent slopes of approximately 1300-1500 m (4000-4500 ft). Those slopes would allow, at a walking speed of 1.34 m/s, load carriage bouts of 15 to 20 min. TEC identified YTC as the best study location, with 17 potential sites. A USARIEM team visited YTC in 1997 and recommended 3 sites at YTC with 4%, 8% and 12% grades. During coordination with YTC, potential problems concerning military and particularly armored vehicle columns led to a second site visit and the replacement of the 8% grade site with an alternate 8.6% grade. The team also selected an abandoned airstrip as a paved, level site. The 4% and 8.6% sites were graded gravel roads, whereas the 12% grade site was more of a track, less uniform in slope, with a rougher surface including some loose rocks up to approximately 12 cm in diameter.

The testing on different slopes (Table 1) was to occur in 9 sessions (4 mornings and 5 afternoons), over 5 days. Each volunteer was to attempt 3 load carriage tests or exercise bouts (1 each, while carrying no load, 13.6 kg [30 lbs] and 27.2 kg [60 lbs]) for the 7 test conditions. Those conditions were 3 uphill and 3 downhill slopes, plus the paved level condition. The grades tested were 0% (level), 4%, 8.6% and 12%. The volunteers carried the loads in a randomly assigned order during each session. Due to the logistics of setting up and moving test sites, testing could be conducted at only 1 slope or grade per day, starting with the level site. An option of repeating 1 test bout

per subject per day was allowed to adjust for an equipment failure or other compromise of the test methods.

Table 1. Description of test sites at Yakima Training Center (YTC)

Site description, length (surface type)
Level, 0% grade, 3000 ft in length (paved)
4% grade, 4500 ft. in length (gravel)
8.6% grade 4000 ft. in length with consistent slope (gravel)
12% grade, 4000 ft. (gravel)

Each 20 min exercise bout was separated by at least a 40 min rest period. All exercise bouts were paced at $1.34 \text{ m}\cdot\text{s}^{-1}$ (3 mph). Initial testing began on the level site to enable subjects to become familiar with the test equipment. No more than 4 subjects participated during a given test bout.

Clothing for all exercise bouts consisted of the Battledress Uniform (BDU), combat boots and field cap. The loads were carried in an issue (ALICE) field pack that weighs 2.8 kg with a frame. Total weight of clothing, pack and oxygen monitor was approximately 8.8 kg. Each volunteer walked for 13-20 min at a time.

For safety monitoring, any exercise bout was stopped before completion if a subject's heart rate reached 210 bpm, or had been sustained at 90% of the individual's maximum heart rate for 5 min, as determined during VO_2max testing. A testing bout could also have been terminated if the medical or test staff deemed it necessary for any reason; or the volunteer felt, in any way, unable or unwilling to continue walking. Testing would also have been stopped if a subject's core temperature had reached 38.5°C or WBGT was 26°C (78°F).

Data Collection

A Sensormedics 2900 (Yorba Linda, CA) metabolic measurement cart was used during the VO_2max test. During the outdoor exercise bouts, Oxylog portable oxygen consumption monitors (P.K. Morgan, Ltd., Gillingham, Kent, England) were used to collect data. Before exercising, each volunteer was fitted with a nose clip, and a mouthpiece attached to a hose directing expired gases to the Oxylog. Heart rates were measured with a sports watch heart rate monitor (Cardiosport® Heart Rate Monitor, Healthcare Technology, Ltd, Tangmere, West Sussex, UK) to provide both data and safety monitoring. Core temperature was measured with a telemetric temperature pill which was swallowed (CorTemp™, Human Technologies, Inc, St. Petersburg, FL). The pill signal was displayed on a small hand-held receiver/data logger receiver (Personal Electronic Devices, Inc., Wellesley, MA). Oxygen uptake, heart rate and core temperature were

hand-recorded every minute during the exercise bouts. Subject weight, age and height were obtained at the time of VO_2max testing. Body weights, with underwear, were obtained on each test day prior to testing.

FIELD TEST SCHEDULE

The basic test plan was to record physiological values for subjects as they walked at a steady 1.34 m/s pace on varying slopes while carrying a pack with a load of zero, 13.6 kg or 27.2 kg. The test plan was that each subject would carry each load once per day in both up and downhill (3x2) directions for a maximum of 20 min. Each 13-20 min load carry was considered a test run/bout. We planned a maximum of 7 load carriage bouts (including 1 make-up) per subject per day. On the level site, subjects were to carry each load once on the paved runway. Testing was conducted at only 1 site per day. Subjects were to be tested in alternating groups of 4, so each subject had at least a 40 min break between test runs. A test matrix was designed so that presentation of loads was counterbalanced, but no more than 2 subjects ever carried the same pack load during the same data collection run.

Each test run consisted of up to 4 subjects wearing the BDU uniform, combat boots and field cap carrying an LC-1 (ALICE) frame and pack with either no load (zero), 13.6 kg (30 lbs) or 27.2 kg (60 lbs) of lead shot in 1 l plastic bottles. Each individual was monitored with a sports watch style heart rate monitor, a telemetric temperature pill and a portable oxygen monitor. Data were hand-recorded every minute. The 1.34 m/s pace was set with a measuring wheel (Master Measure MM50, Rolatape® Corporation, Spokane, WA) modified with a bicycle cyclometer (Enduro 2 CC-ED200, Cateye Company, Ltd, Boulder, CO). Weather conditions were measured with a Wet-Bulb Global Temperature (WBGT) monitor that displayed air, black globe and natural wet-bulb temperatures, plus a calculated WBGT value.

MODELING

Based on the laboratory data, a model (12) was developed for uphill and downhill load carriage energy costs, which started with an estimate of level load carriage costs (W_L) derived from Passmore and Durnin (9). Several uphill load carriage models are already available, including Pandolf et al. (8), but to fit with the estimate of W_L , separate equations were developed for positive (W_P) and negative (W_N) vertical displacement. The equations are:

$$\begin{array}{ll} W_L = 3.28m_t + 71.1 & [W] \\ W_P = 3.5 (m_tgh/s) & [W] \\ W_N = 2.4 (m_tgh/s) 0.3^{(\alpha/7.65)} & [W] \\ W_{UP} = W_L + W_P & [W] \\ W_{DWN} = W_L + W_N & [W] \end{array}$$

Where m_t is the total mass displaced (nude body weight, clothing, pack, instruments and load) in kg, g is the acceleration due to gravity ($9.8 \text{ m}\cdot\text{s}^{-2}$), and h is the vertical displacement per second at 1.34 m/s in m for a given grade. Alpha (α) is the angle of

the slope for a given grade. The conversion from W to $\text{ml O}_2/\text{kg}/\text{min}$ was based on 2.87 divided by the nude body mass.

RESULTS

SUBJECT POPULATION

Population variables (mean \pm sd) for the 8 male subjects were age (24 ± 4 yr), height (174 ± 7 cm) and weight (80.2 ± 9.9 kg). Maximum oxygen uptake (VO_2max) was 51.61 ± 4.62 mlO₂/min/kg. Percent body fat was $20.5\pm 4.7\%$. Table 2 lists individual values.

Table 2. Subject population dimensions

Subject	Age yr	VO ₂ max mlO ₂ /kg/min	Weight kg	Height cm	Body Fat %
1	28	44.58	83.5	171	24.2
2	23	49.34	63.8	163	22.7
3	20	56.92	84.1	177	12.2
4	23	48.29	80.5	171	21.8
5	23	53.15	93.8	187	22.6
6	30	49.62	75.5	168	21.6
7	22	52.41	89.7	178	24.5
8	19	58.58	70.8	175	14.1
Mean	24	51.61	80.2	174	20.5
s.d.	4	4.62	9.9	7	4.7

STUDY CONDITIONS

Table 3. Weather condition during data collection

MAY DATE	TIME BEGIN (PDT)	TIME END (PDT)	MEAN T _A \pm SD (°C)	MIN T _A (°C)	MAX T _A (°C)
2	14:33	19:27	17.4 \pm 0.7	16.1	18.9
3	09:18	16:36	11.7 \pm 1.5	7.8	14.7
4	10:18	16:00	12.7 \pm 1.4	9.8	15.1
5	09:36	16:18	12.3 \pm 1.8	7.9	15.9
6	09:23	16:11	11.2 \pm 1.7	7.8	14.5
MEAN VALUES			13.1 \pm 2.5	9.9 \pm 3.6	15.8 \pm 1.8
PDT = PACIFIC DAYLIGHT TIME					

The study design was based in part on an assumption that the most significant environmental problem would be warm conditions that, in combination with exercise, could result in heat injuries. Actual environmental conditions ranged from neutral to cold (Table 3).

OXYLOG PERFORMANCE

Eight Oxylogs (6 Oxlog 2, 2 Oxlog 1) were brought for the study. Due to the late arrival of the equipment shipment, we experienced some problems with battery charging on the first day. Throughout the study, we experienced difficulty with the Oxylog reliability. We attributed this in part to the study conditions and problems associated with field operations. The Oxylogs were attached to rucksacks with up to 27.2 kg loads, and the process of moving, lifting and removing the packs created conditions considerably more severe than most laboratory or outdoor testing.

DATA MATRIX

As a consequence of the difficulty of maintaining 4 simultaneously functioning oxygen monitors, testing proceeded much more slowly than planned. The first day of testing at the paved runway started late and was completed as dusk arrived. One subject was unable to participate in early testing due to a non-study related condition. We then attempted to obtain a complete matrix for the 8.6% grade. This required 2 days instead of the 1 scheduled day. Only 4 subjects were able to complete the uphill 13.6 kg carry, and only 2 completed the 27.2 kg carry. With the remaining 2 days, we collected all downhill data on the 4% grade, plus 1 uphill series with a zero load pack. The rationale for selecting the zero load for the uphill carry was that we had insufficient time to obtain all the uphill data, and given the fact that only 50% of the subjects were able to complete the 13.6 kg carry on the 8.6% uphill grade, it was unlikely that any subjects would be able to successfully carry a 27.2 or 13.6 kg load up a 12% grade. With continuing failures of the oxygen monitors on the last test day, we were unable to obtain any uphill data on the 12% grade. If all 8 subjects had successfully completed all scheduled bouts, the total number of bouts would have been 168. The actual number of bouts attempted was 122, and 112 were successfully completed by the subjects. No bouts were ended due to the safety limits of core temperature or WBGT. On the 8.6% uphill bouts, a few subjects reached the 90% HR limit, but withdrew prior to sustaining that level for 5 min.

DATA ANALYSIS

Level grade data collection runs were 20 min, whereas data runs on other grades were 13-15 min in duration. We used the average value of each individual's data for the time period of 5-12 min. The initial method of evaluating data was simply to plot the individual and mean data. The most complete data set was for the zero load condition. It was clear, however, from inspecting the individual data that some Oxylog data were incorrect.

The initial response was to remove suspect data by inspection. However, such methodology was extremely subjective, and thus, an effort was made to generate a

systematic data filter. It was decided to base the filter on the 1 min oxygen uptake value ($\text{l O}_2/\text{min}$). Given that all 1 min values were not recorded simultaneously, some subjective adjustments were made in identifying the 1 min values. Once the 1 min or near baseline value was selected for each individual run, the mean and standard deviation (SD) for all runs by an individual subject was calculated. A multiple (1, 1.5 or 1.96) of the individual's SD for the 1 min values was used as a filter by eliminating all data from bouts where the 1 min value exceeded the multiple of the SD. Using the most conservative filter (1.96 SD), only 4 of 112 runs were eliminated, whereas using the more restrictive 1 SD threshold, 32 runs were eliminated. The filter selected (1.5 SD) eliminated 12 data runs (Table 4). The number of excluded data points includes 1 clear outlier not eliminated by the filter. The data set constructed with the 1.5 SD filter was used for all subsequent data analysis (Figure 2).

Figure 2. Oxygen uptake for all loads by grade (1.5 SD filter)

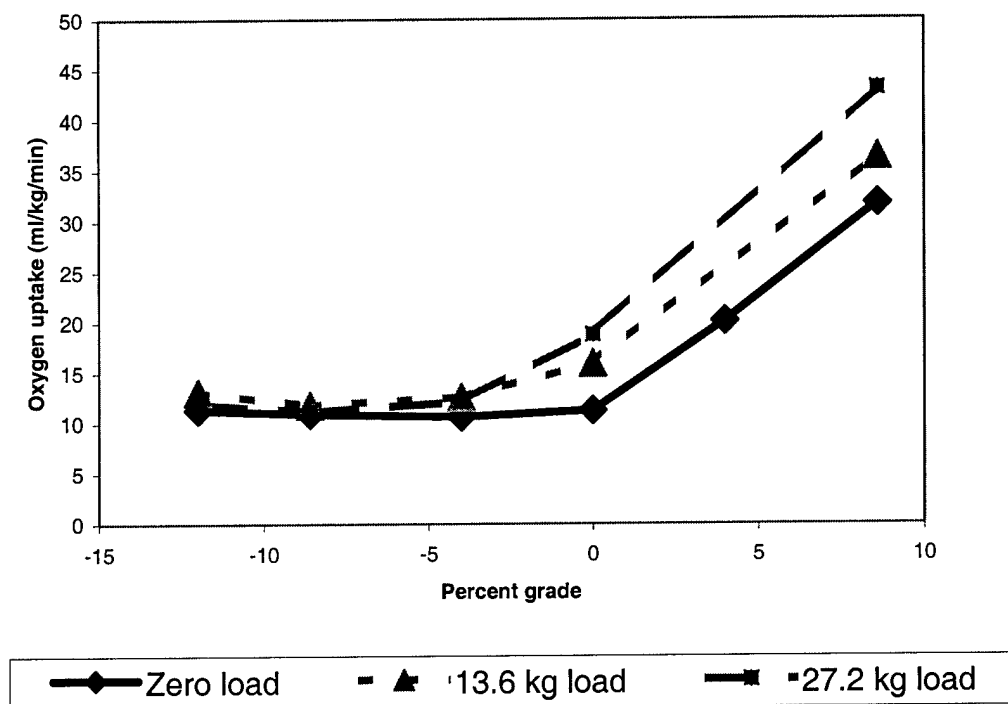


Table 4. Mean oxygen uptake values (mlO₂/kg/min) by load

Zero load									
Grade	Raw data			1.5 SD filter			1 SD filter		
	Mean	±SD	N	Mean	±SD	N	Mean	±SD	N
-12%	11.35	1.49	8	11.35	1.49	8	11.54	1.51	7
-8.6%	10.92	2.13	7	10.92	2.13	7	10.73	2.35	5
-4%	9.69	3.94	8	10.65	3.07	7	11.66	1.67	6
0%	11.38	4.35	7	11.28	4.58	5	16.18	---	2
+4%	20.13	1.88	8	20.13	1.88	8	20.13	1.88	8
+8.6%	32.61	2.91	8	31.75	2.89	6	33.16	2.99	3
13.6 kg (30 lbs) load									
Grade	Raw data			1.5 SD filter			1 SD filter		
	Mean	±SD	N	Mean	±SD	N	Mean	±SD	N
-12%	13.11	1.43	8	13.11	1.43	8	13.11	1.43	8
-8.6%	10.35	3.17	8	11.81	1.90	6	12.58	0.80	3
-4%	12.61	1.34	8	12.61	1.34	8	12.55	1.43	7
0%	16.27	1.79	6	15.97	1.83	5	15.97	2.11	4
+4%	---	---	---	---	---	---	---	---	---
+8.6%	38.26	4.11	4	36.37	1.95	3	36.37	1.95	3
27.2 kg (60 lbs) load									
Grade	Raw data			1.5 SD filter			1 SD filter		
	Mean	±SD	N	Mean	±SD	N	Mean	±SD	N
-12%	14.40	6.78	7	11.94	2.08	6	11.94	2.08	6
-8.6%	12.22	3.90	8	11.16	2.67	7	11.12	3.18	5
-4%	11.01	3.35	8	12.16	0.84	7	12.48	1.04	4
0%	18.81	1.86	7	18.81	1.86	7	18.81	1.86	7
+4%	---	---	---	---	---	---	---	---	---
+8.6%	43.10	---	2	43.10	---	2	43.10	---	2

COMPARISON TO LABORATORY DATA

A direct comparison can be made to the data for the zero load data collected in the field and laboratory (Figure 3). Values for the 8.6% grade were interpolated between the 8% and 10% (12% uphill) grades. To construct a data set for comparison to the field 13.6 kg load, the laboratory values for 9.1 kg and 18.1 kg were averaged (Figure 4). There was no laboratory data to compare to the 27.2 kg field data.

Figure 3. Comparison of field and laboratory results (zero load)

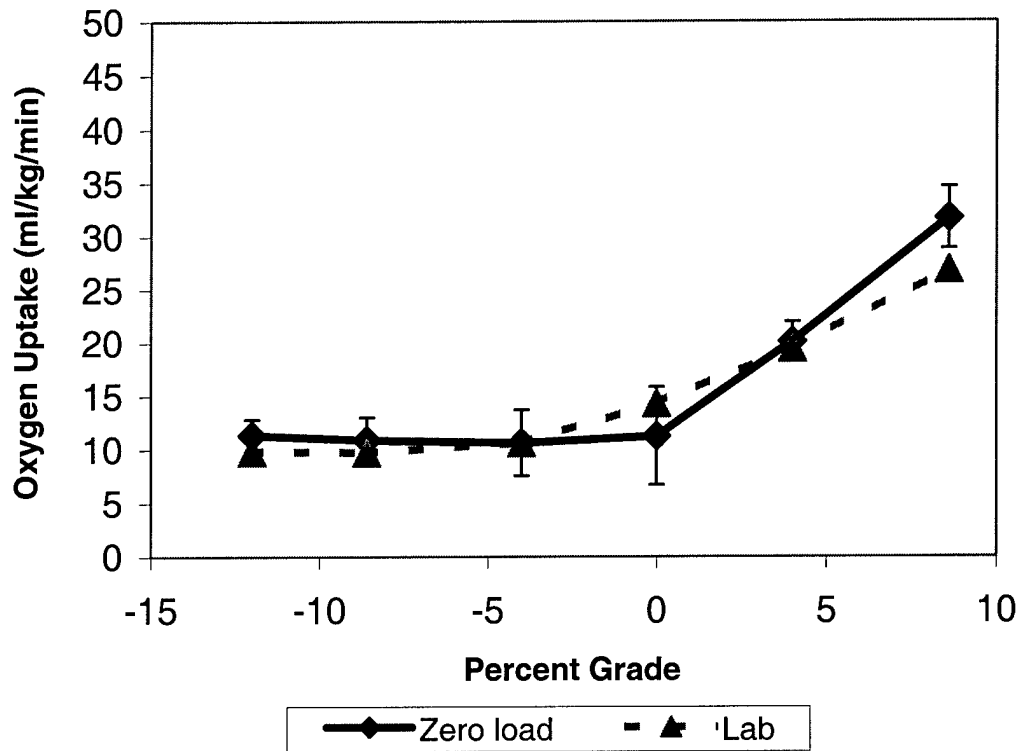
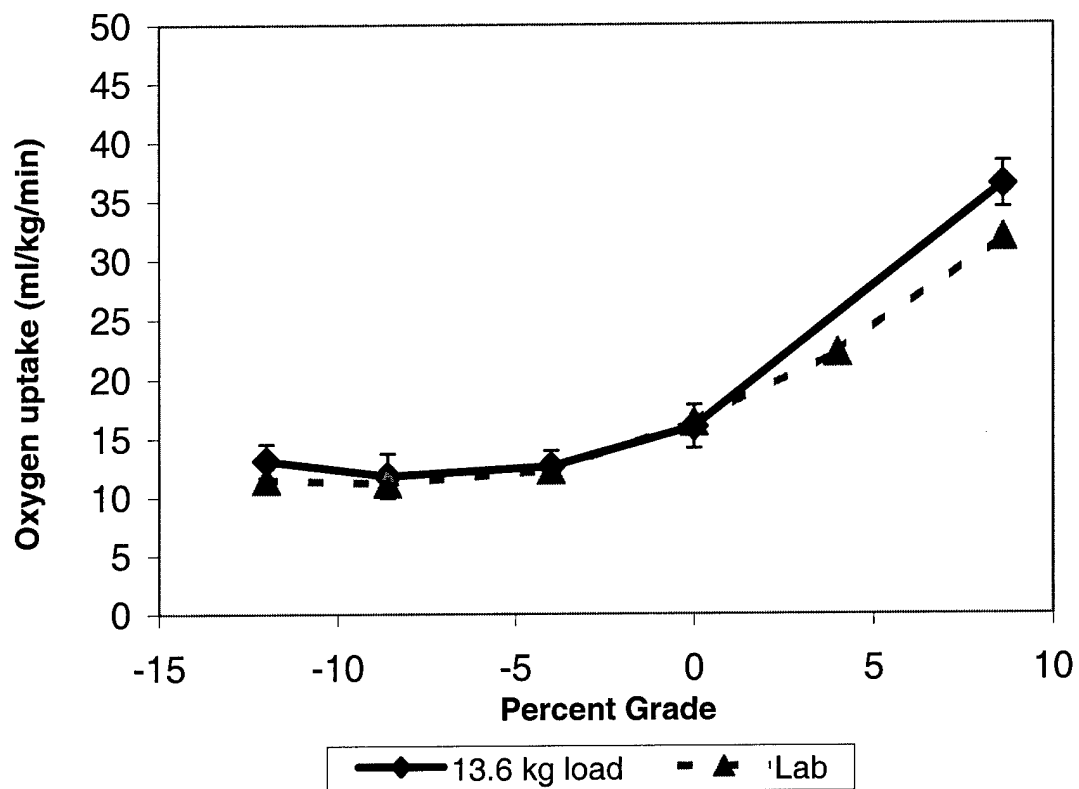


Figure 4. Comparison of field and estimated laboratory results (13.6 kg load)



APPLICATION OF THE TERRAIN FACTOR

A terrain factor of 1.1 for a dirt road is given by Soule and Goldman (13). The laboratory values obtained on a treadmill were multiplied by the terrain factor. Inspection prior to statistical analysis suggests that the 1.1 dirt road correction factor may be low for the Yakima gravel roads. Soule (personal communication, 2000) indicates that the terrain factor for a dirt road was derived from measurements on a compacted soil surface as opposed to a gravel surface. There is also a suggestion, looking at the tail values of -12% and +8.6% grade, that the terrain factor may not be linear.

MODELING VALUES

As noted previously, the model is based on the subject's nude weight, plus 8.8 kg for clothing, equipment and instruments, plus whatever load was carried in the ALICE pack. In addition, modeling values are calculated using only input for individuals who participated in the specific bout to calculate the mean field data. Thus, for level walking with zero load, data were entered for 5 subjects. When the mean value was calculated by entering individual weights, it was also possible to calculate an SD for each modeling value. Thus, an estimate of the expected minimum variability due to subject variability may be calculated (Table 5).

Statistical results

For statistical analysis, data were divided into 3 sets. One set incorporated all data for negative slopes, plus level walking data for all 3 loads (n=81). The second data set incorporated all uphill, plus level walking data for the no (zero) load condition (n=19). The third data set included all uphill data for the 8.6% grade (n=8). Measured values were compared to values calculated with the model using the corresponding data (individual weights, load and slope). The variable "type" indicates a comparison between measured vs. modeling values.

Results for the negative data set found no significant difference between the measured vs. the downhill modeling results. Load and grade were highly significant overall, and there were significant interactions for grade vs. load and grade vs. type, thus indicating that data points for load and grade were discrete.

Results for the single (zero) load, multi-slope data set also indicated no significant differences between measured and calculated values. For the uphill, no-load subset, grade and the interaction between grade and type were highly significant. For the 8.6% grade with all loads, load and type were significant. Thus, for the 8.6% uphill grade, there was a significant difference between the measured and model calculated values.

Table 5. Field data and model calculations

Zero load – no terrain factor						
Grade	1.5 SD filter			Model		
	Mean	±SD	N	Mean	±SD	N
-12%	11.35	1.49	8	9.86	0.46	8
-8.6%	10.92	2.13	7	10.03	0.46	7
-4%	10.65	3.07	7	11.32	0.48	7
0%	11.28	4.58	5	14.58	0.50	5
+4%	20.13	1.88	8	20.79	0.60	8
+8.6%	31.75	2.89	6	25.33	0.35	6
13.6 kg (30 lbs) load (1.1 terrain factor)						
Grade	1.5 SD filter			Model		
	Mean	±SD	N	Mean	±SD	N
-12%	13.11	1.43	8	10.94	0.60	8
-8.6%	11.81	1.90	6	11.01	0.39	6
-4%	12.61	1.34	8	12.57	0.65	8
0%	15.97	1.83	5	16.15	0.87	5
+4%	---	---	---	---	---	---
+8.6%	36.37	1.95	3	28.71	0.86	3
27.2 kg (60 lbs) load (1.1 terrain factor)						
Grade	1.5 SD filter			Model		
	Mean	±SD	N	Mean	±SD	N
-12%	11.94	2.08	6	12.13	0.75	7
-8.6%	11.16	2.67	7	12.23	0.80	7
-4%	12.16	0.84	7	13.83	0.87	7
0%	18.81	1.86	7	18.03	0.99	7
+4%	---	---	---	---	---	---
+8.6%	43.10	---	2	35.76	---	2

Inspection of Figures 5, 6 and 7 clearly indicate that measured values were higher than model based values. The trend holds for all 3 loads. Based solely on the statistical results, the uphill portion of the model may be invalid. However, Figures 3 and 4, which compare oxygen uptake ($\dot{V}O_2$) values measured in the laboratory on a metabolic cart with data collected with Oxylog monitors in the field, indicate the same trend. Montoye et al. (6) indicate that Oxylog monitors have a tendency toward greater errors for high (and low) metabolic rates, which may account for the difference between field data and both laboratory and modeled values on steeper grades. It is also possible that slippage increase on steeper slopes and a linear or constant terrain factor is incorrect.

In relation to the large increases in energy costs with increasing uphill grade, the difference in cost between downhill grades is small. The differences in energy consumption for downhill load carriage could therefore be represented by a constant value for a given speed, dependent only on load for grades 4%-12%.

Figure 5. Comparison of field data to modeling results (zero load)

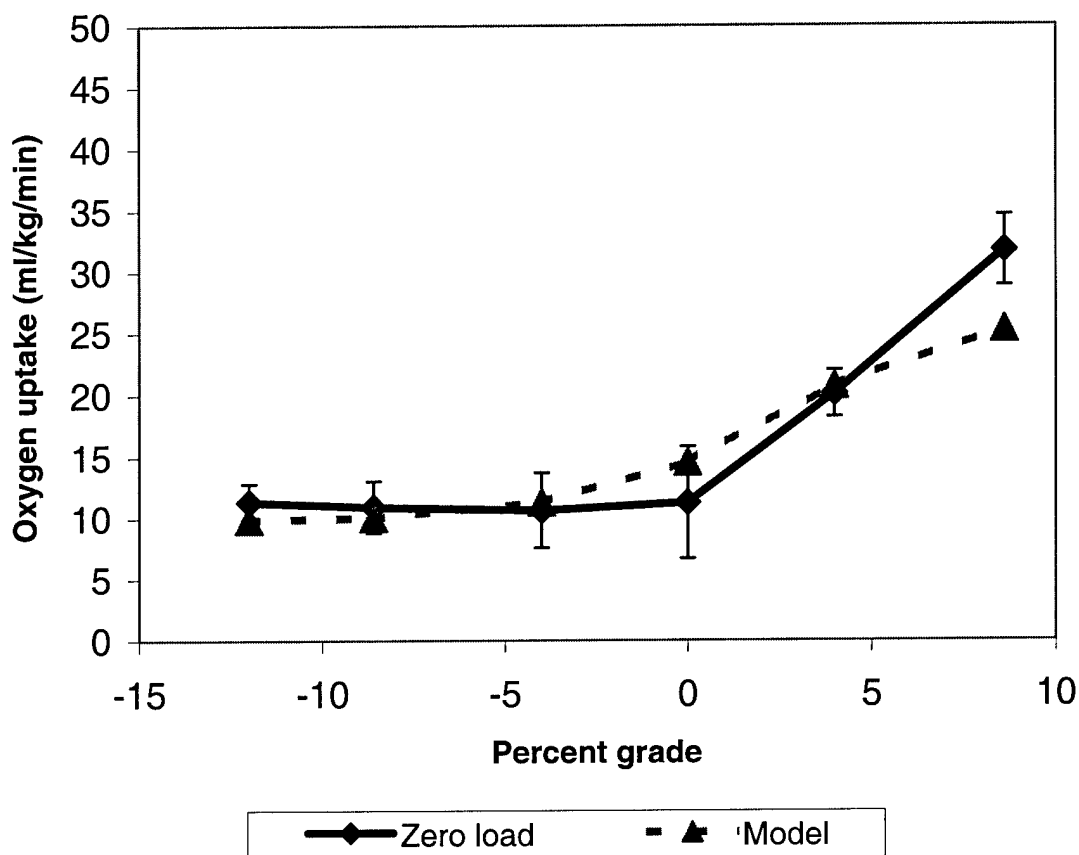


Figure 6. Comparison of field data to modeling results (13.6 kg load)

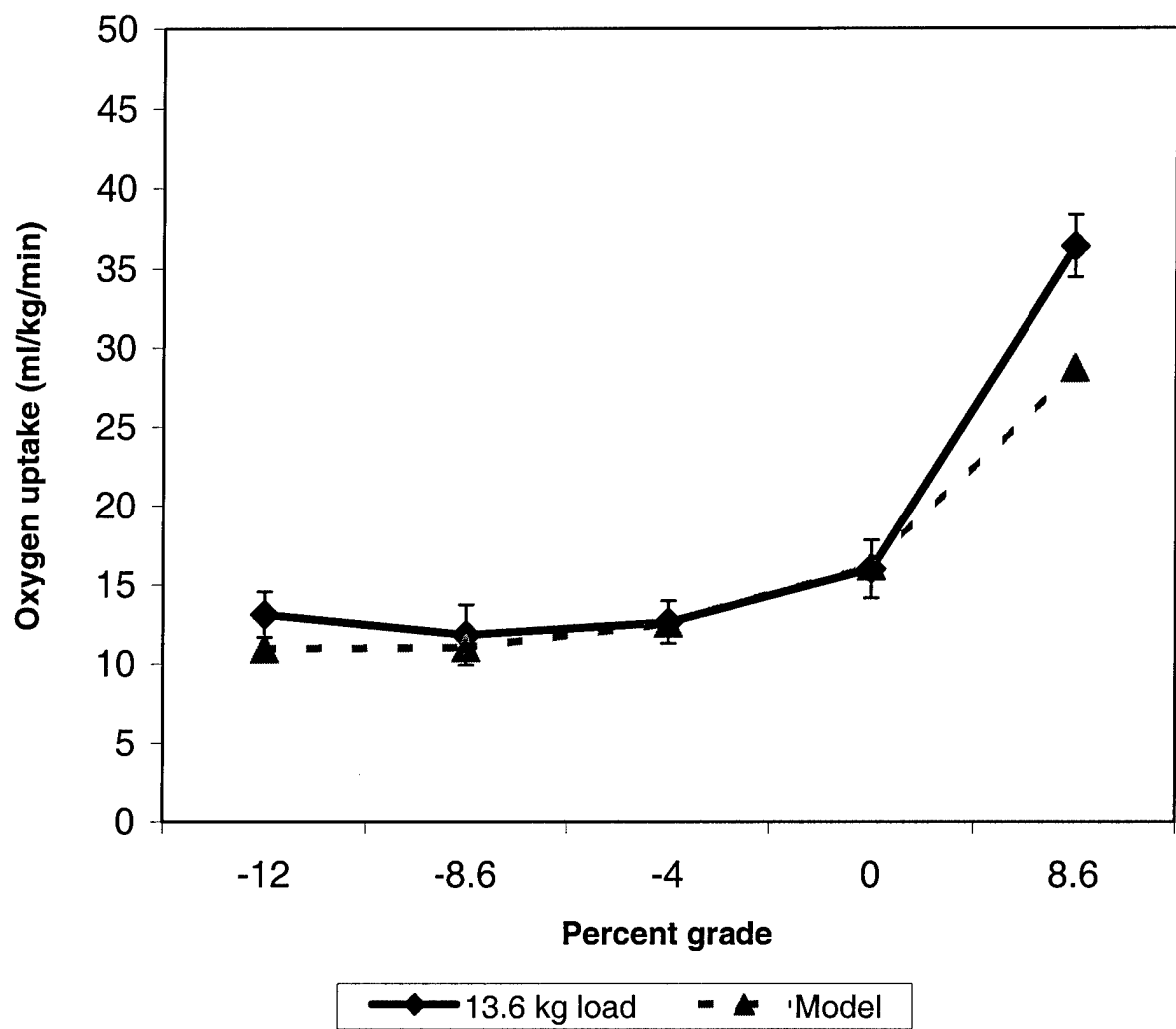
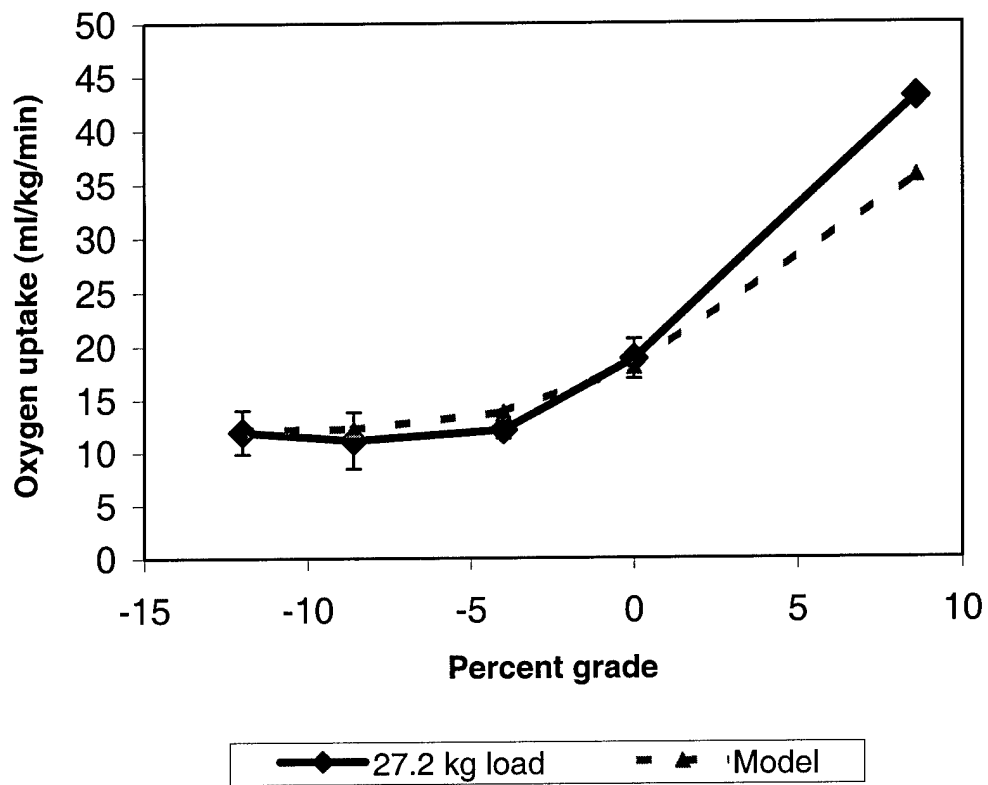


Figure 7. Comparison of field data to modeling results (27.2 kg load)



DISCUSSION

Statistical analysis of the fit between the YTC field data and values calculated with the Santee et al. (12) model supports the validity of the downhill portion of the model, whereas the results for the uphill modeling are ambiguous. The relatively high variability of the field data reduces the credibility of both the positive validation of the downhill model and the negative results for the uphill 8.6% grade. Higher variability would be expected in any shift from the controlled laboratory environment to the field. Overall, control of test conditions, including grade, surface uniformity, walking speed and instrumentation, was reduced in the field.

The problems experienced with the Oxylog monitors may, in part, be attributed to operating conditions in the field. The instruments may have been subjected to harsher handling while attached to the packs than would normally be expected, making it more difficult to maintain instrument function at remote locations. A portion of the operational problem was the continuing effort to have 4 functional monitors for each bout, rather than testing 1 or 2 subjects at a time. It was not uncommon to have a logger malfunction while waiting to bring all 4 loggers on line.

As noted by Montoye et al. (6), Oxylog values have increasing errors relative to standard instruments at higher and lower range metabolic rates, with the least error at approximately 4 MET. Based on mean VO_2 values, the MET range for this study was 3 to 11 MET, so instrument-based errors in VO_2 were more likely on steeper, uphill grades.

Application of the 1.1 terrain factor improved the fit between laboratory treadmill data and field data collected on rougher surfaces (Figure 3, 4). The divergence of field and laboratory at the tails of the plot indicate the possibility that the terrain factor may not be a linear constant. The large difference between measured and model estimated values for the uphill 8.6% grade data might be due to a loss of traction on steeper slopes. It is also possible that the fit of the model to the field data could have improved if a slightly higher terrain factor for gravel, as opposed to the 1.1 value for a packed dirt surface, had been used. On the 12% grade, we encountered an additional confounding element for the terrain factor--a mixed size distribution of gravel and rocks that presented an irregular surface. More effort was required to maintain balance or stability on the rougher, mixed surface. As noted, the variability of field data makes it difficult to move from inference to more concrete analysis.

The possible effect of irregular surfaces is the essence of maintaining lateral stability--avoiding deflection off the linear direction or losing balance. The energy cost or penalty of maintaining lateral stability is a product of an inefficient stride or counter-balancing movements of the upper body. Relative to the cost of braking to counter acceleration due to gravity, the cost of maintaining lateral stability may be small. The overall cost of maintaining stability--resisting excessive acceleration and lateral deflection--may be countered in part by the dampening effect of the load. As a result, for a given walking speed, an individual with a pack load of 13.6 kg may in fact be more stable than either a person with no load, who must combat lateral instability or deflection, or a person with a 27.2 kg load, who must counter primarily excess acceleration...

In attempting to quantify total energy costs during activities over varied terrain, Hoyt (personal communications, 2000) assumed movement involving downhill terrain required the same energy cost as level walking. As observed for the laboratory data (12), in relation to the large increases in energy costs with increasing uphill grade, the difference in cost between downhill grades is small. The difference in energy consumption for downhill load carriage could be adequately represented by a constant value for a given speed and load for grades 4%-12%, with little loss in accuracy for the overall energy costs of movement. Consequently, an unreliable estimate or model of uphill load carriage is of greater importance to calculating energy consumption than an inaccurate downhill modeling element.

CONCLUSIONS

The downhill portion of the model derived from laboratory data fit the YTC field data when the terrain factor was used in conjunction with the model on non-paved surfaces. The results also supported the validity of the uphill equation when modeling results were compared to data for level and uphill load carriage with an unloaded pack, but that data set was based on a limited population (N=19). In a similar manner, the model did not adequately predict the VO_2 of uphill load carriage on an 8.6% grade, but that data set was also small (N=8). The greater variability of field data make inferences based on the fit between the field data, laboratory data and modeling results less definitive unless the potential sources of variability are taken into consideration. The lack of fit between the 8.6% uphill grade data and modeling estimate may, in part, reflect a limitation of the oxygen uptake monitor at relatively high MET levels.

RECOMMENDATIONS

The database should be expanded to include different (slower) walking speeds. USARIEM investigators (personal communications, Obusek, Patton, Harman, 1998) have indicated that backpack loads up to 61 kg (135 lbs) are realistic operational loads, and that military units are requesting information concerning the carriage of heavy loads. Greater loads may require different packs or load carriage systems. Data should be collected on more surface types, such as dirt or loose sand. The oxygen monitors should be upgraded to a system that is more reliable under field conditions. A 5 min standing baseline should be incorporated into the exercise bouts to establish a value for comparison between bouts. Instability during downhill movement occurs whenever forward momentum increases or lateral deflection occurs. One interesting possibility is that carrying a load may increase the resistance to acceleration, while a heavier load may reduce the likelihood of lateral deflection. Both excessive acceleration and deflection may require additional energy to maintain stability. An intermediate load of perhaps 13.6 kg may dampen both effects, and thereby be more stable than either a person with no load or with a 27.2 kg load for a given walking speed. Such a relationship may also change with varying walking speeds and surfaces. Laboratory treadmill testing should be done prior to deployment, thereby ensuring familiarity with methods, and providing a set of values collected under more controlled conditions for comparison to field data.

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